

# PHYSICAL PROGRAMM AND ACCELERATION OF POLARIZED LIGHT NUCLEI BEAMS AT JINR NUCLOTRON

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## Abstract

The physical spin program at high  $p_T$  region and energies  $s_{NN}^{1/2} \sim 10 \text{ GeV}$  is discussed. It's shown that cumulative processes, color transparency problem and polarization phenomenons directly connect with properties new form of the nuclear matter as Color Quark Condensate(CQC). Studies of CQC one of the most important physical problem and can be realized using polarized ion beams at JINR nuclotron-M (and in future at NICA). The calculations of spin resonance strengthes in the linear approximation for p, d, t and  $^3\text{He}$  beams in the JINR nuclotron are presented. The methods to preserve the degree of polarization during crossing the spin resonances are examined. The method of matching the direction of polarization vector during the beam injection in to the ring of the nuclotron is given. These methods of spin resonance crossing can be used to accelerate polarized beams in the other cyclic accelerators.

In the recent decades occurred the radical revision our understanding of forms of the nuclear matter which can be realized at different temperatures and densities [1]. Nowadays it is predicted that at low temperatures and high densities the nuclear matter is formed completely the new form, in which the dominant role play the constituent quarks. This state can be named as a Quark Color Condensate (QCC). The properties of this form of nuclear matter determine the physical properties of matter in the center of massive stars and, possibly, it is directly connected with the riddles of the explosions of supernovas. The discovered enormous magnetic fields in stars (up to  $\sim 10^{17} \text{ T}$ ) can lead to the fact that the Quark Color Condensate (QCC) will be polarized. Therefore the polarization characteristics of super-dense nuclear matter not only are interesting by themselves, but they have important significance to developing the theory of evolution of massive stars.

Is it possible to obtain nuclear matter at the high densities and low temperatures in a laboratory? Studies of cumulative (subthreshold) processes have shown that we observe the processes, in which nuclear matter exist at low temperatures and densities which exceed the ordinary nuclear (hadron) density up to ten times [2]. The density three times greater then ordinary density was observed in the processes of the deep inelastic scattering (DIS) of electrons on the nuclei in JLAB [3]. Studies of cumulative processes and DIS processes have shown that the high density state with a certain probability exists in the ordinary nuclei (the fact that it is not the product of compression during the collision was shown by study of the special features of cumulative processes and lepton DIS processes at  $x$  up to 3, because lepton cannot compress the nuclear matter).

It means that in the nuclear matter exist nucleon clusters (Blokhintsev had named its as fluctons) with the density several times higher than usual and there is no energy gap for

the transition to the QCC phase. Most likely in the region at low temperature and high density for the nuclear matter there is not first-order transition. If we take additionally in to account the absence of the first-order transition in the region of high temperatures it can be considered as the indication for the nuclear matter generally there are not regions of the first-order transition. This is a picture of the phase transition of nuclear matter which was popular in the 90's years of the last century [1].

The high  $p_T$  processes (region of  $x_T \sim 1$ ) deal with the high density of the nuclear (hadron) matter too. The color transparency (CT) (observed for the first time in 1988) [4] and elastic  $p - p$  cross-sections in the singlet and triplet spin states at angles  $90_{cm}^\circ$  (middle of 70th) [5] may be the most interesting phenomenons.

The cumulative processes and processes with high  $p_T$  in the range of energies up to  $\sqrt{s_{NN}} \sim 10 \text{ GeV}$  is possible to describe well using phenomenological approaches based on the constituent picture only not polarization characteristics. However till now we can say that there are not complete understanding ("microscopic" models) of the nature of discovered effects. Especially difficultly to explain the nature of polarization effects. It means that there are very poor understanding of properties of the nuclear matter at high densities and low temperatures. Very important properties all these phenomenons that its not vanish at high energy region. Moreover some features very close to new phenomenons. Let us compare CT data [4] with data from RHIC for the so-called "jet quenching" effect (Figure 1). We can see very close shape of the CT data and the RHIC data. That's why we can say that the nature of high  $p_T$  suppression at RHIC directly connect with the nature of CT phenomena.

Before we have said that the cumulative effects and high  $p_T$  effects have been discovered in the energy range up to  $\sqrt{s_{NN}} \sim 10 \text{ GeV}$ . JINR nuclotron is the accelerator of relativistic nuclei which works and continues to be improved in the V.I. Veksler and A.M. Baldin Laboratory of high energies(LHE). The accelerator uses the magnets with superconductor coils developed in LHE and has been created to work with proton beams up to energy  $12 \text{ GeV}$  and nuclei up to  $6 \text{ AGeV}$ . In JINR is discussing plan to built new collider NICA with maximal energy  $\sqrt{s_{NN}} = 9 \text{ GeV}$ . The first stage to NICA project will be upgrade of the nuclotron to the nuclotron-M. Polarized light ion beams will be important part of this new project. With polarized ion beams we will have real possibility to resolve many problems connected with CQC properties there are:

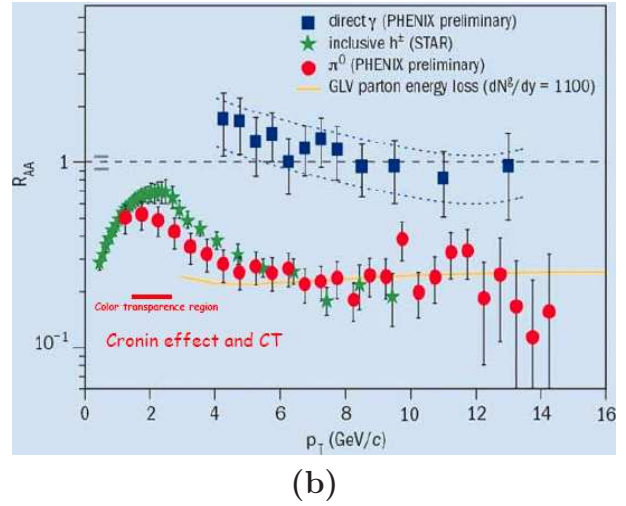
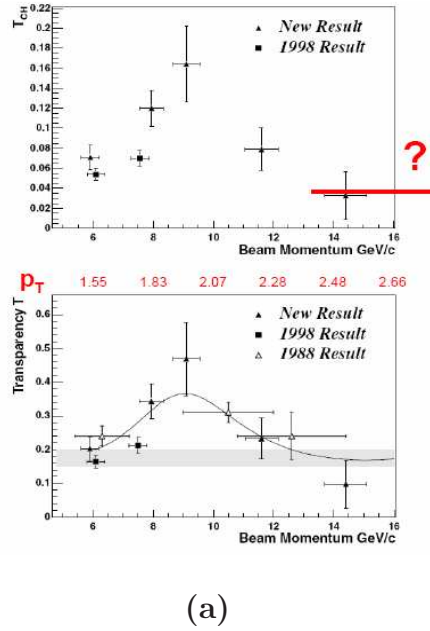
- resolve the "spin crisis" of 70s using complete set polarized states  
( $p \uparrow - p \uparrow, p \uparrow - n \uparrow, n \uparrow - n \uparrow, \dots$ );
- understand the nature of color transparency phenomenon  
( $p \uparrow - A, p \uparrow - {}^3\text{He}(d) \uparrow$ );
- understand the nature of cumulative(subthreshold) particle production;
- the first time study the properties of polarized nuclear matter  
( $d \uparrow - d \uparrow, {}^3\text{He} \uparrow - {}^3\text{He} \uparrow$ ).

As the first step to realize this programm we will need to know details of the spin dynamic in the nuclotron-M.

Complete description of spin dynamic in circular accelerators can be realized using concept of a periodic precession axis  $\vec{n}(\theta)$ , which is periodical function of generalized azimuth  $\theta$ :  $\vec{n}(\theta) = \vec{n}(\theta + 2\pi)$  [6, 7].

Spin motion on the equilibrium orbit is a precession around the axis  $\vec{n}$ : the spin projection  $J = \vec{s}\vec{n}$  on the axis  $\vec{n}$  will be conserved and a transversal projection to  $\vec{n}$  is turn to the angle  $\Psi = 2\pi\nu$ . Spin frequency  $\nu$  is shown the turn number of the particle spin during one turn of particle in an accelerator. In traditional accelerator with the transverse master field (nuclotron is the accelerator this type) the precession axis  $\vec{n}$  is parallel to the vertical axis. The spin frequency  $\nu$  will changing in proportion to the particle energy:  $\vec{n} = \vec{e}_z$ ,  $\nu = G\gamma$ , where  $\gamma$  — the relativistic factor,  $G = (g - 2)/2$  — anomalous part of the gyromagnetic ratio. Main characteristic to describe the collective spin motion of particle beam is a polarization vector  $\vec{\Pi} = \langle \vec{s} \rangle = \langle J\vec{n} \rangle$  and a power of depolarization  $D = D = 1 - |\vec{\Pi}|$ . The angular brackets define that we take averaging over particle distribution in the beam.

The motion of particles on non-equilibrium orbits give deviation (spread) of precession axes  $\Delta\vec{n}$  and spread spin frequencies  $\Delta\nu$ . If we inject beam of polarized particles in to the nuclotron with a spin perpendicular to the precession axis  $\vec{n}$  during the "time"  $\theta \sim 1/\Delta\nu$  (for the nuclotron it is a some hundreds tunes) will be full randomization spin directions related to the axis  $\vec{n}$  and polarization will be lost fully. Therefore we need to match the polarization vector of the beam with the direction precession axis  $\vec{n}$  (vector of polarization must be parallel to the axis  $\vec{n}$ ). The existing channel of transportation have not this coordination. After the ion source the polarization vector is directed to the vertical direction. The vector polarization is not changing direction in the linac. During transportation to the nuclotron the rotation of polarization vector take place in vertical and in horizontal planes. As a result the direction of the vector of polarization will have the angle  $\alpha_z$  with vertical axis ( see Table 1). The power of depolarization for not correct



**Figure 1a.** The CT data from [4]. **Figure 1b.** RHIC data for "jet quenching" effect.

matchings is

$$D_{inj} = 2 \sin^2 \frac{\alpha_z}{2}.$$

For eliminating this effect will be enough, for example, install the pair of the solenoids at the beginning and the end of the transport channel which do not influence the particle trajectory and same time will turn polarization vector to the vertical line.

	$^1H$	$^2H$	$^3H$	$^3He$
$\alpha_z$ , degree	67	9.8	116	79
$D_{inj}$ , %	62	1.5	55	81

Table 1: The power of the beam depolarization at some mismatching of polarization during injection in the nuclotron.

Degree of polarization in the process of acceleration can changes in region of the spin resonance, when spin frequency becomes equal to

$$\nu = \nu_k, \quad \nu_k = k + k_z \nu_z + k_x \nu_x + k_\gamma \nu_\gamma. \quad (1)$$

where  $\nu_x$  and  $\nu_z$  are betatron frequencies,  $\nu_\gamma$  is frequency of synchrotron motion. The values of betatron frequencies are equal  $\nu_x = 6.8$ ,  $\nu_z = 6.85$  for the nuclotron.

The most strongest there are resonances of linear approximation, which include intrinsic resonances and resonances of structural imperfections: integer, nonsuperperiodical and the coupling resonances of  $x$  and  $z$  oscillations.

Intrinsic resonances appear when spin interact with the betatron motion. Remaining resonances are connected with the distortion of the magnetic structure of the rings which are caused by inaccuracies in production and misalignment of the structural elements, with the nonlinear effects of spin and orbital motions, with switching of corrective and functional elements(dipoles, quadrupoles, sextupoles and s.o.).

Table 2 shows the number of linear resonances for different particle beams  $^1H$ ,  $^2H$ ,  $^3H$ ,  $^3He$  in the nuclotron ( $k$  and  $m$  — integer,  $p = 8$  — number of superperiods).

Resonance type	Resonance condition	Number of resonances			
		$^1H$	$^2H$	$^3H$	$^3He$
Intrinsic resonances	$\nu = k p \pm \nu_z$	6	—	8	9
Integer resonances	$\nu = k$	25	1	32	37
Nonsuperperiodical resonances	$\nu = k \pm \nu_z (k \neq m p)$	44	2	55	64
Coupling resonances	$\nu = k \pm \nu_x$	49	2	63	73

Table 2: Linear resonances in the ring of the nuclotron.

The spin frequency grows proportionally to energy with acceleration of beam and the intersection of spin resonances becomes unavoidable. The basic parameters for crossing the spin resonance are the spin resonance strength  $w_k$ , detuning from the resonance  $\varepsilon = \nu - \nu_k$  and speed of detuning changing  $\varepsilon' = d\varepsilon/d\theta$  (speed of crossing). The spin resonance strength  $w_k$  is the corresponding Fourier-harmonic of transverse spin disturbance  $\vec{w}$  and determines the width of dangerous interval in region of the spin resonance.

We can distinguish three possibility to cross the resonance with constant speed there are fast, adiabatic and intermediate crossings. The beam practically completely will be depolarized with the intermediate crossing of resonance ( $|w_k|^2 \sim \varepsilon'$ ). With the fast intersection ( $|w_k|^2 \ll \varepsilon'$ ) the polarization vector  $\vec{\Pi}$  hasn't time to considerably change and the degree of depolarization is equal to  $D \simeq (\pi \langle |w_k|^2 \rangle) / \varepsilon'$ . With the slow (adiabatic) crossing when ( $|w_k|^2 \gg \varepsilon'$ ) take place overturn of the polarization vector relative to the vertical direction. In this case should be distinguished the case of "coherent" and "incoherent" crossing. "Coherent" crossing means that the resonance strength is identical for all particles (integer resonances). In this case the condition ( $w_k^2 \gg \varepsilon'$ ) is satisfied for all particles of the beam and degree of polarization after crossing remains with exponential accuracy. With the "incoherent" crossing the resonance strength is different for different particles and, for example, it depends on the amplitude of betatron oscillations (intrinsic resonances). There are not only particles with adiabatic type crossing in the beam, but the intermediate and fast types of crossing, which leads to the partial depolarization of the beam. With the normal distribution of particle coordinates and momentums in the beam the degree of depolarization will be equal:  $D \simeq \varepsilon' / (\pi \langle |w_k|^2 \rangle)$ . With the adiabatic crossing it is necessary to consider the synchrotron oscillations of the particles, whose accounting can lead to the partial or even complete depolarization.

It is convenient for calculations to introduce new parameter as the characteristic resonance strength  $w_d = \sqrt{\varepsilon' / \pi}$ . Intersection of the spin resonance lead to practically the complete depolarization of the beam when the resonance strength is equal to  $w_d$ . Then the resonance strength, which corresponds to loss by 1% of polarization with the fast crossing, is equal to  $0.1 w_d$ , and the resonance strength, which corresponds to loss by 1% of polarization with the adiabatic crossing, is equal to  $10 w_d$  ("incoherent" resonances),  $3.26 w_d$  ("coherent" resonances).

The results of calculation of main characteristics for crossing of the spin resonances and their strengthes are given in Table 3 [8, 9].

	$^1H$	$^2H$	$^3H$	$^3He$
G	1.793	-0.143	7.92	-4.184
$E_k^{\max}$ , [GeV/u]	12.84	6.00	3.74	8.28
$\nu_{min} - \nu_{max}$	1.8 – 26.3	-1.05 – -0.144	7.92 – 39.5	-41.1 – -4.19
$\varepsilon'$ , ( $\tau_{\text{accel}} = 0.5s$ )	$7.0 \cdot 10^{-6}$	$2.8 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$
$w_d$ , ( $\tau_{\text{accel}} = 0.5s$ )	$1.5 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$

Table 3: Crossing characteristics of the spin resonances in the nuclotron.

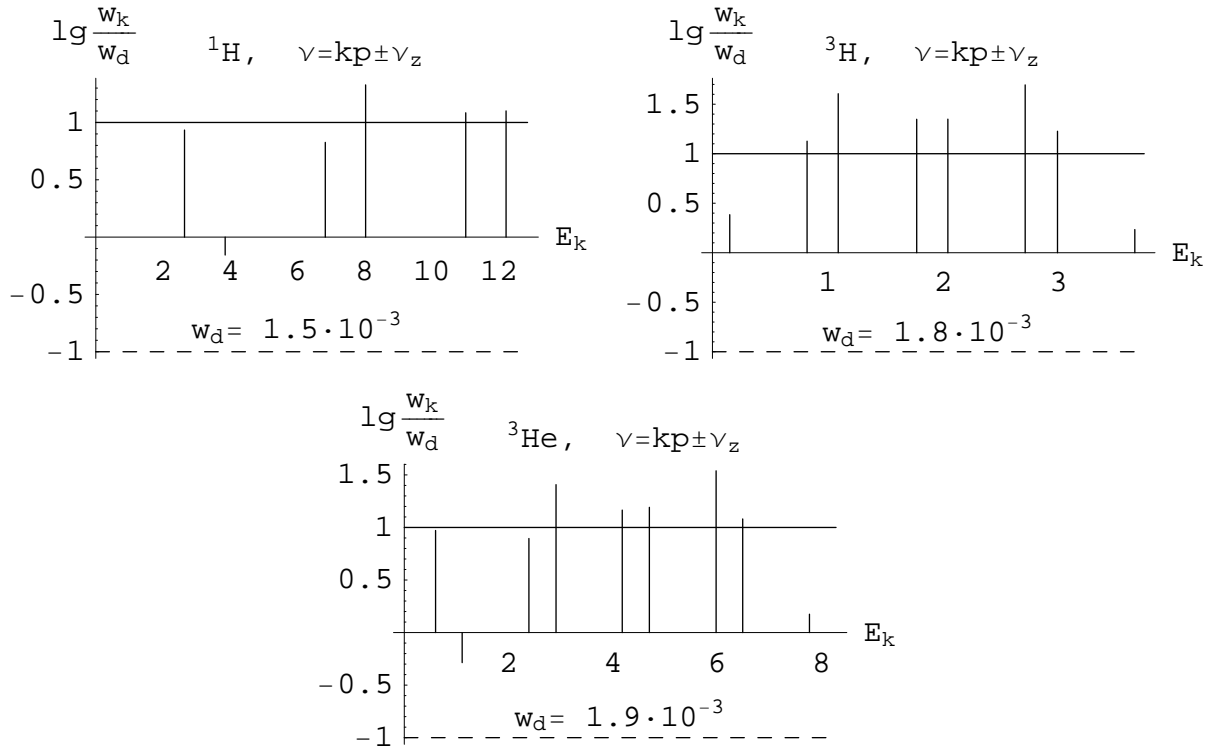


Figure 2: Intrinsic resonances.

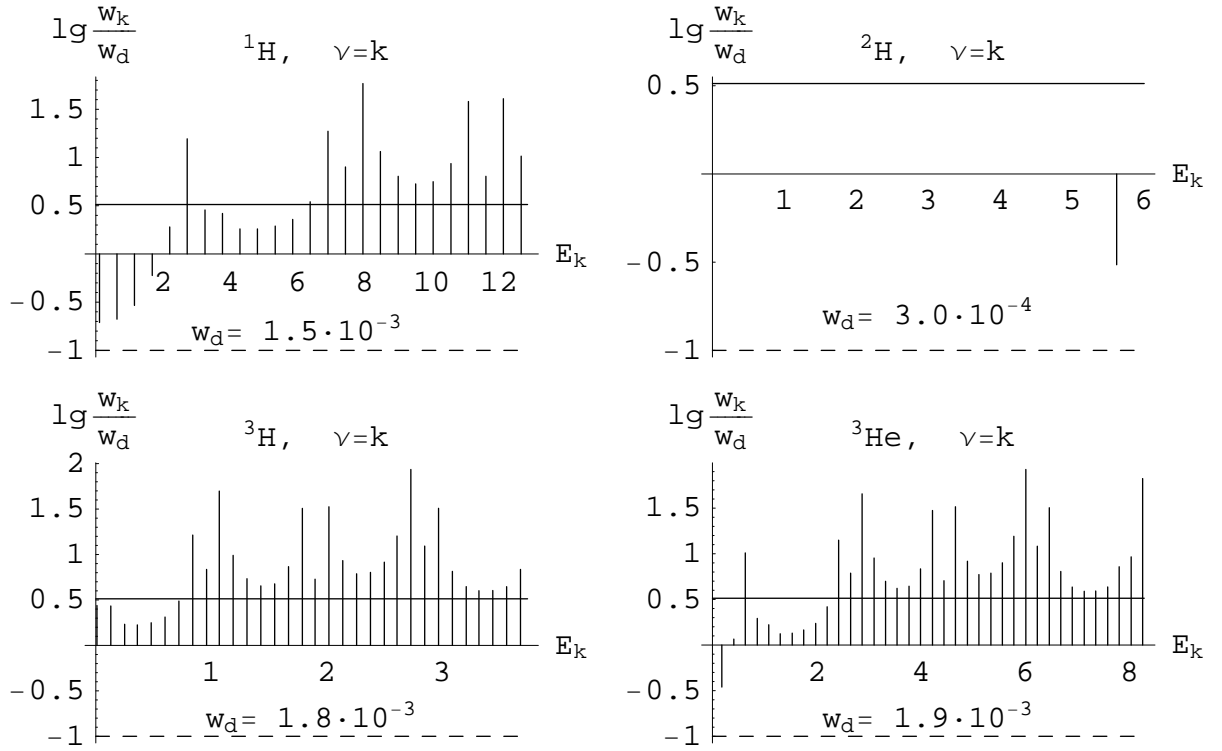


Figure 3: Integer resonances.

Figures 2-3 show the logarithmic graphs of the resonance strengthes of linear approximation in units of the characteristic strength  $w_d$  in the operating range of beam kinetic energy  $E_k$ . Each graph is split into three regions, which correspond to the intermediate crossing (region between the continuous and dotted lines), fast crossing (under the dotted line) and adiabatic crossing (above the solid line). It was assumed in calculation of the resonance strengthes that the emittances in the horizontal and vertical direction at the energy of injection there are equal  $45\pi \text{ mm} \cdot \text{mrad}$ , adjustment errors of quadrupoles — 0.1 mm and adjustment errors of the turning for main magnets — 0.001 rad.

The resonances located in the zone of intermediate crossing lead to the depolarization of the beam. From the comparison of graphs it follows that almost in full of energy range the depolarization take place for intrinsic and integer resonances (Figure 2-3). The coupling resonances and nonsuperperiodical resonances also can lead to the depolarization of the beam in the same regions of energy where intrinsic resonances are located.

Let us consider methods of crossing of the spin resonances the most suitable for the nuclotron. In crossing of the integer resonances with the intermediate strength ( $|w_k|^2 \sim \varepsilon'$ ) it is expedient to use a method of premeditated increasing of the resonance strength [7]. For this purpose it is enough to insert in free nuclotron gaps some longitudinal magnetic field. The resonance strength with this longitudinal field is determined by expression

$$w_k = \frac{\varphi_y}{2\pi} = \frac{(1 + G)H_y L_y}{2\pi H R}$$

and must be correspond to the condition of the adiabatic crossing  $|w_k|^2 \gg \varepsilon'$ . Furthermore in order to avoid the effects of depolarization because of synchrotron modulation of energy necessary to satisfy also the condition:  $|w_k|^2 \gg \sigma \nu_\gamma \sim 10^{-2}$ , where  $\sigma = \nu \sqrt{\langle (\Delta\gamma/\gamma)^2 \rangle}$  — the amplitude of synchrotron modulation of energy, and  $\nu_\gamma$  — the frequency of synchrotron oscillations [9].

The maximal values of integrals of the longitudinal field (on the energy of extraction) which need to guarantee the adiabatic crossing of the integer resonances in full range of the energy are given in Table 4.

	$^1H$	$^2H$	$^3H$	$^3He$
$(H_y L_y), \text{ T} \cdot \text{m}$	1	3.4	0.3	0.9

Table 4: The integrals of the longitudinal field for the adiabatic crossing.

When crossing the resonances with the betatron frequencies it is possible to use a method of compensation the degree of depolarization [10]. Conservation of the degree of polarization is ensured due to control of detuning  $\varepsilon = \nu - \nu_k$  inside the resonance region. The control of detuning  $\varepsilon$  during crossing is possible due to changing the spin frequency  $\nu$ . For this it is necessary to introduce into the ring of nuclotron an "insert" with an additional magnetic field which makes it possible to obtain the required dependence of the spin frequency on a magnetic field  $\nu = \nu(\vec{H})$ . There is possible to use the "insert" with the longitudinal and radial fields, depicted in Figure 4, where  $\varphi_x, \varphi_y$  — angles of spin turns around the radial and the longitudinal fields.



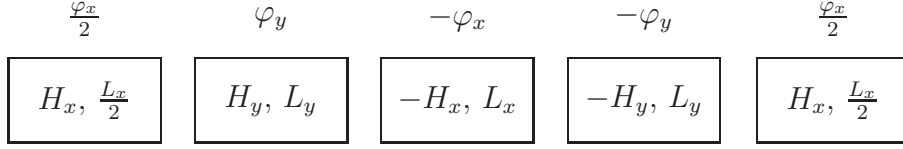


Figure 4: The "insert" to control the spin frequency.

In the approximation of a small spin angular turn ( $\varphi_x, \varphi_y \ll 1$ ) the direction of the equilibrium polarization remains vertical and changing of the precession frequency of the spin is equal to  $\Delta\nu = (\varphi_x \varphi_y)/(2\pi)$ . The maximal vertical deviation of the equilibrium orbit caused by radial fields will be  $\Delta z_{\max} = \varphi_x/(8\nu)(4L_y + 5L_x)$ . The maximal length of the "insert" is limited by the length of free space in the accelerator which in the nuclotron is about 350 cm.

The depolarization of beam is possible during the slow beam extraction from the nuclotron when the energy of the beam close to energy of the spin resonances. The degree of depolarization in this case depends on the spin resonance strength  $w_k$  and the detuning from the resonance  $\varepsilon$ . For the completely polarized beam at the beginning power of depolarization will be:  $D \simeq \frac{\langle w_k^2 \rangle}{2\varepsilon^2}$ . In this case to avoid depolarization one need move away from the resonance to the value  $\Delta\varepsilon \sim 10w_k$  ( $\Delta\gamma = \Delta\varepsilon/G$ ). For example, for the beam of protons this value will be  $\Delta\gamma \simeq 50\text{MeV}$  for the detuning from the resonance with the strength  $w = 10^{-2}$  (adiabatic crossing) and  $\Delta\gamma \simeq 5\text{MeV}$  for the dutuning from the resonance with the strength  $w = 10^{-3}$  (intermediate crossig).

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